Title: Measurement of Spectrum of Radiation from Horizon of Analog Black Hole

Date: Jul 23, 2013 11:00 AM

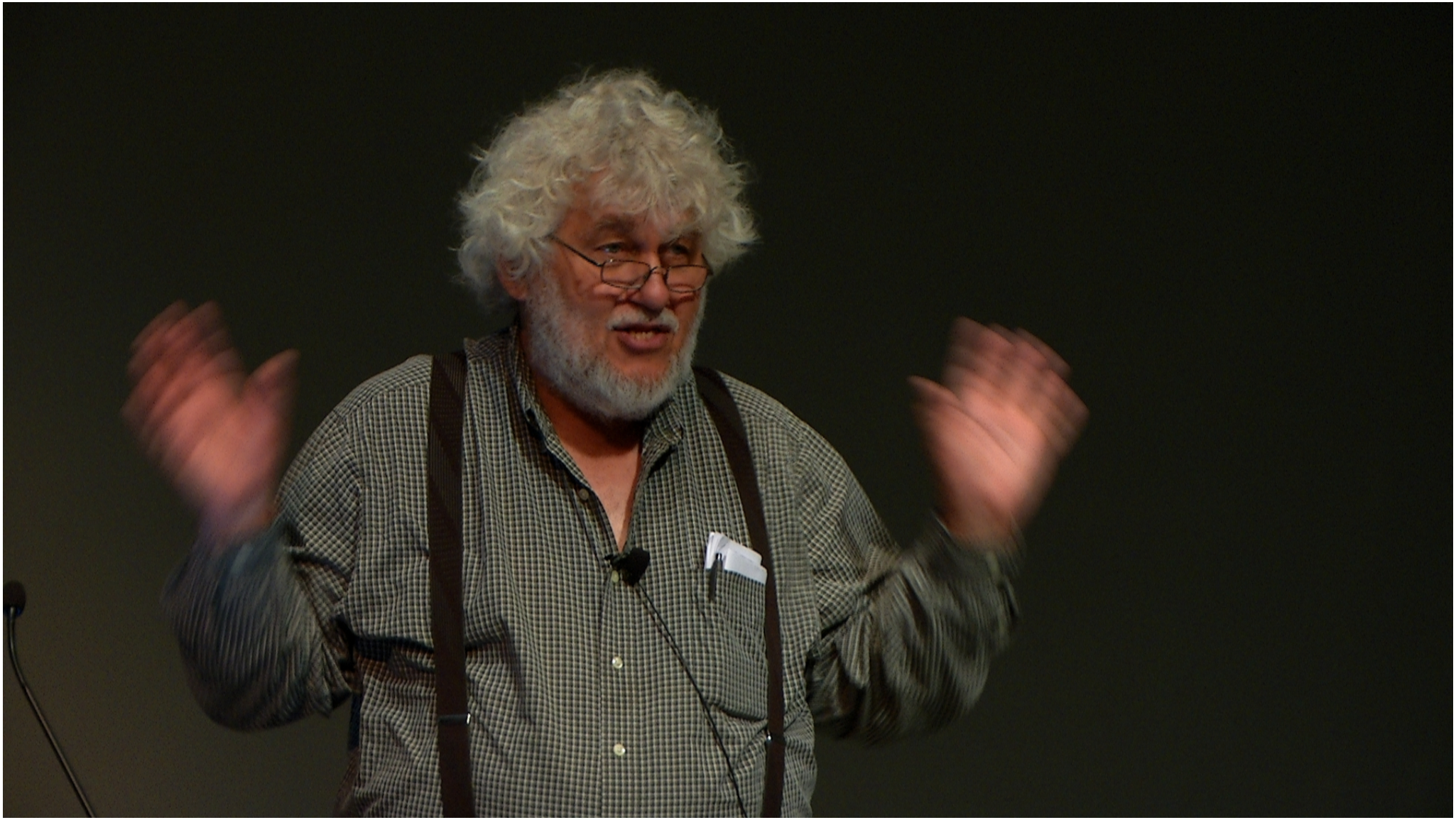
URL: http://pirsa.org/13070049

Abstract:

Measurement of Spectrum of Radiation from Horizon of Analog Black Hole

W.G.Unruh

gr-qc:1008.1911
PRL 106, 021302 (2011)



Bekenstein suggested (1972)black holes have an entropy
Based in part on Area increase thm by Hawking and Christodulou.
Parody the arguement
"Since Area increases and Entropy increases
Area ≈ Entropy"

In fact he had arguments that the entropy is proportional to area. But most floundered on fact that black hole have zero temperature, whereas since area depends on Energy, temperature should be non-zero

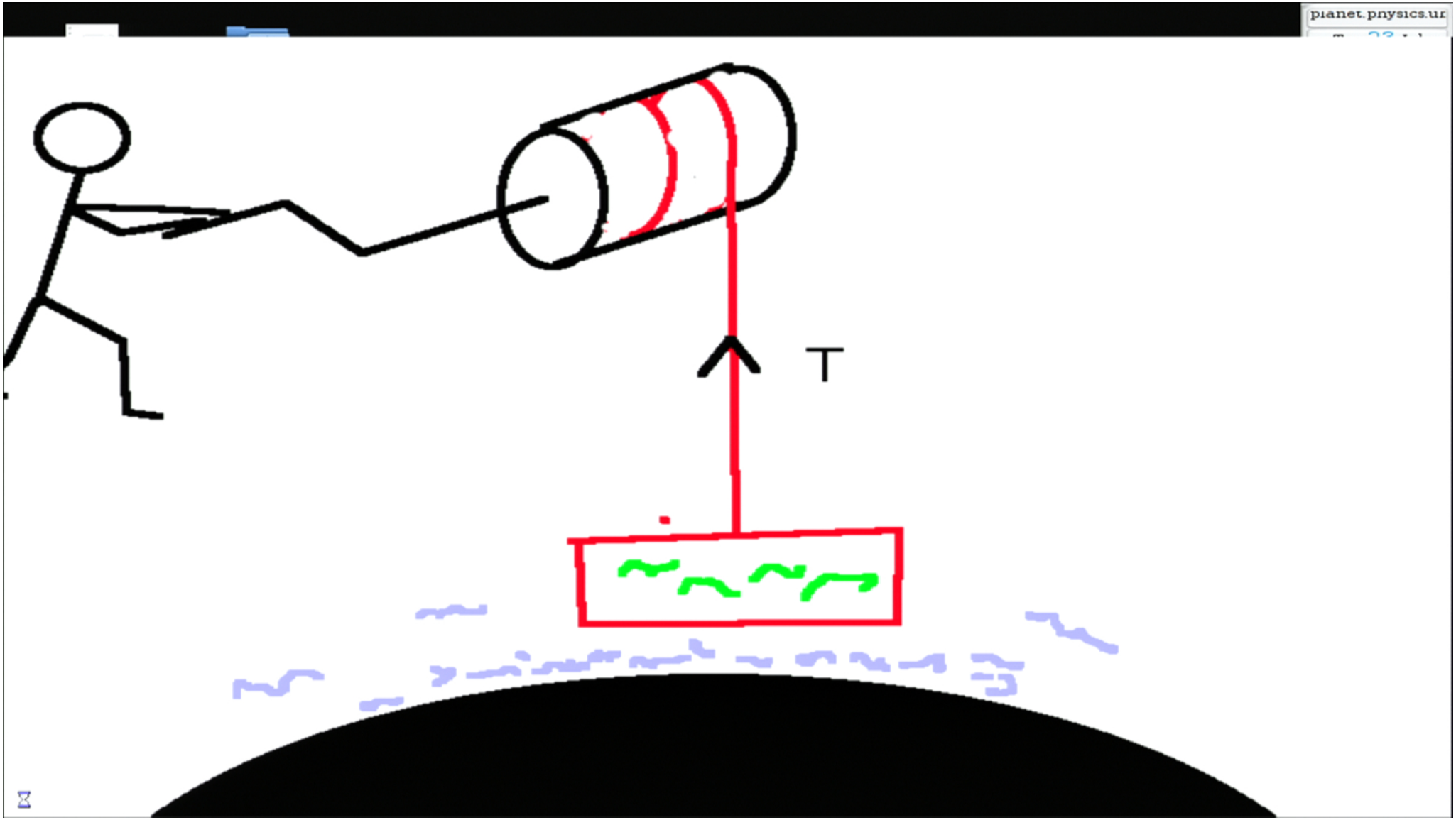
Bad Analogy

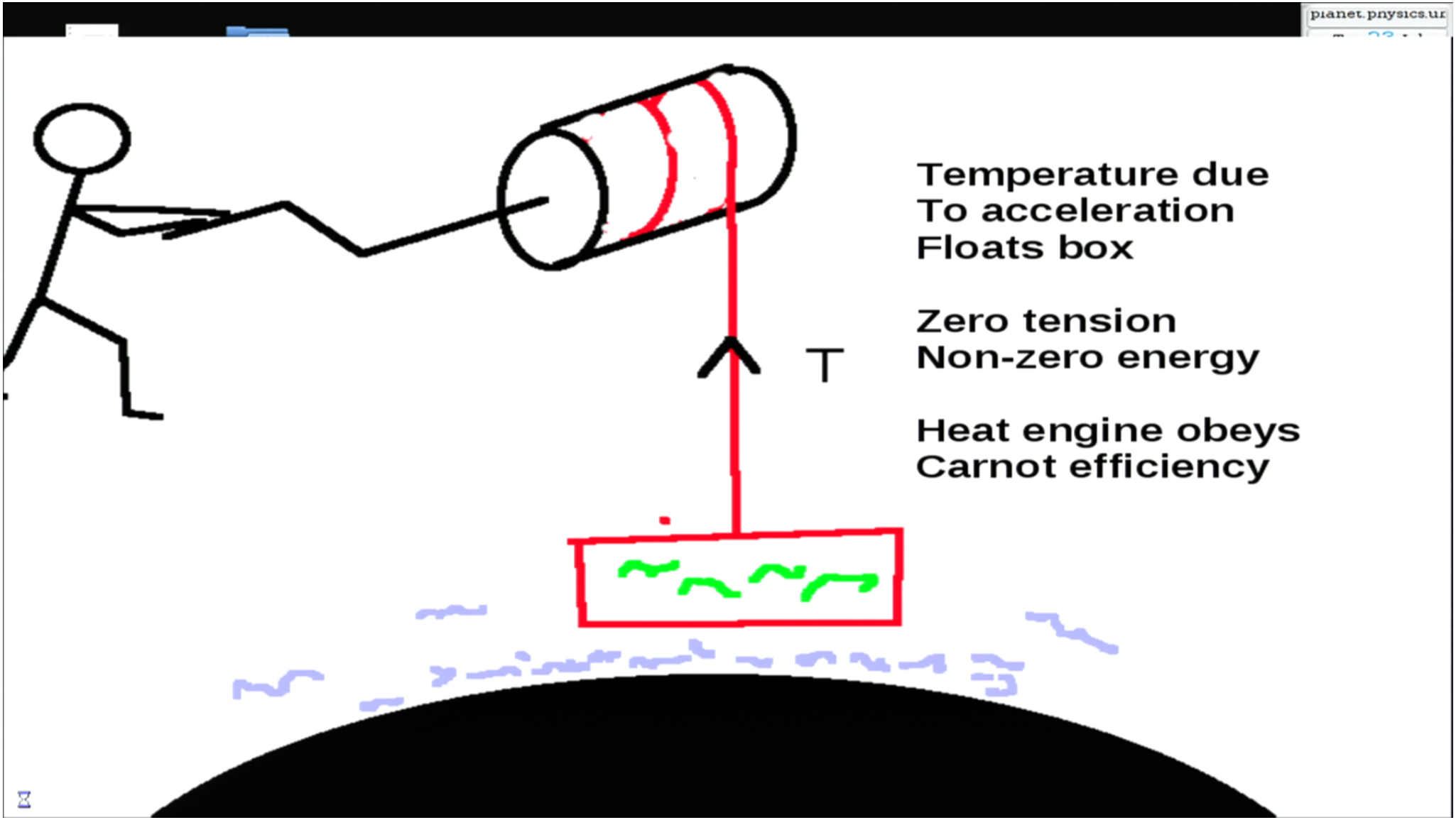
But right?

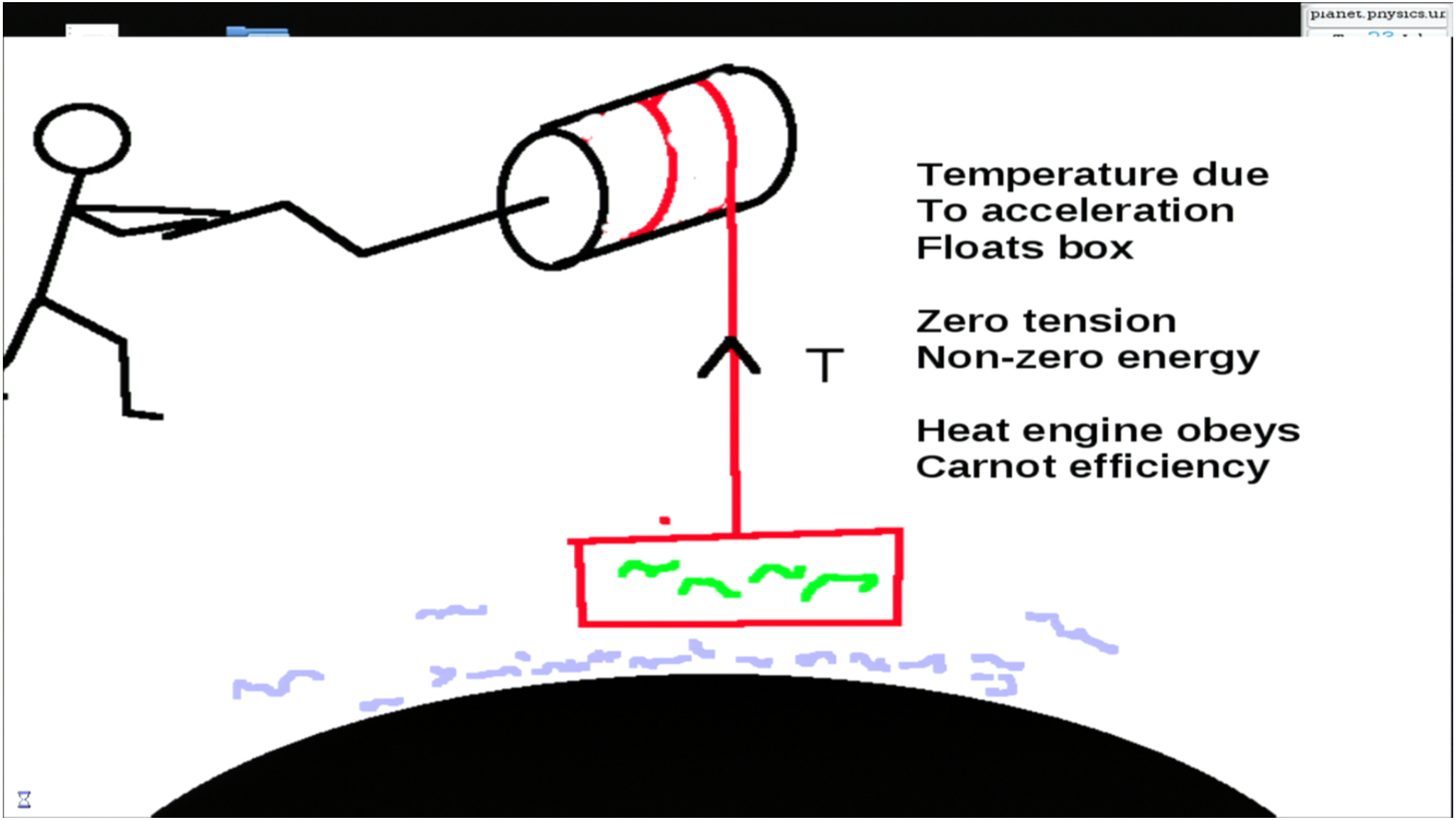
Black Hole evaporation

1974-- Hawking "predicted" that black holes were not black but had a temperature

$$T = \frac{1}{8\pi M}\left(\frac{c^3\hbar}{k_B G}\right)$$


planet.physics.ur
T


planet.physics.ur
T
Temperature due
To acceleration
Floats box
Zero tension
Non-zero energy
Heat engine obeys
Carnot efficiency


planet.physics.ur
T
Temperature due
To acceleration
Floats box
Zero tension
Non-zero energy
Heat engine obeys
Carnot efficiency

What is the entropy

Controversy – Is entropy Statistical?

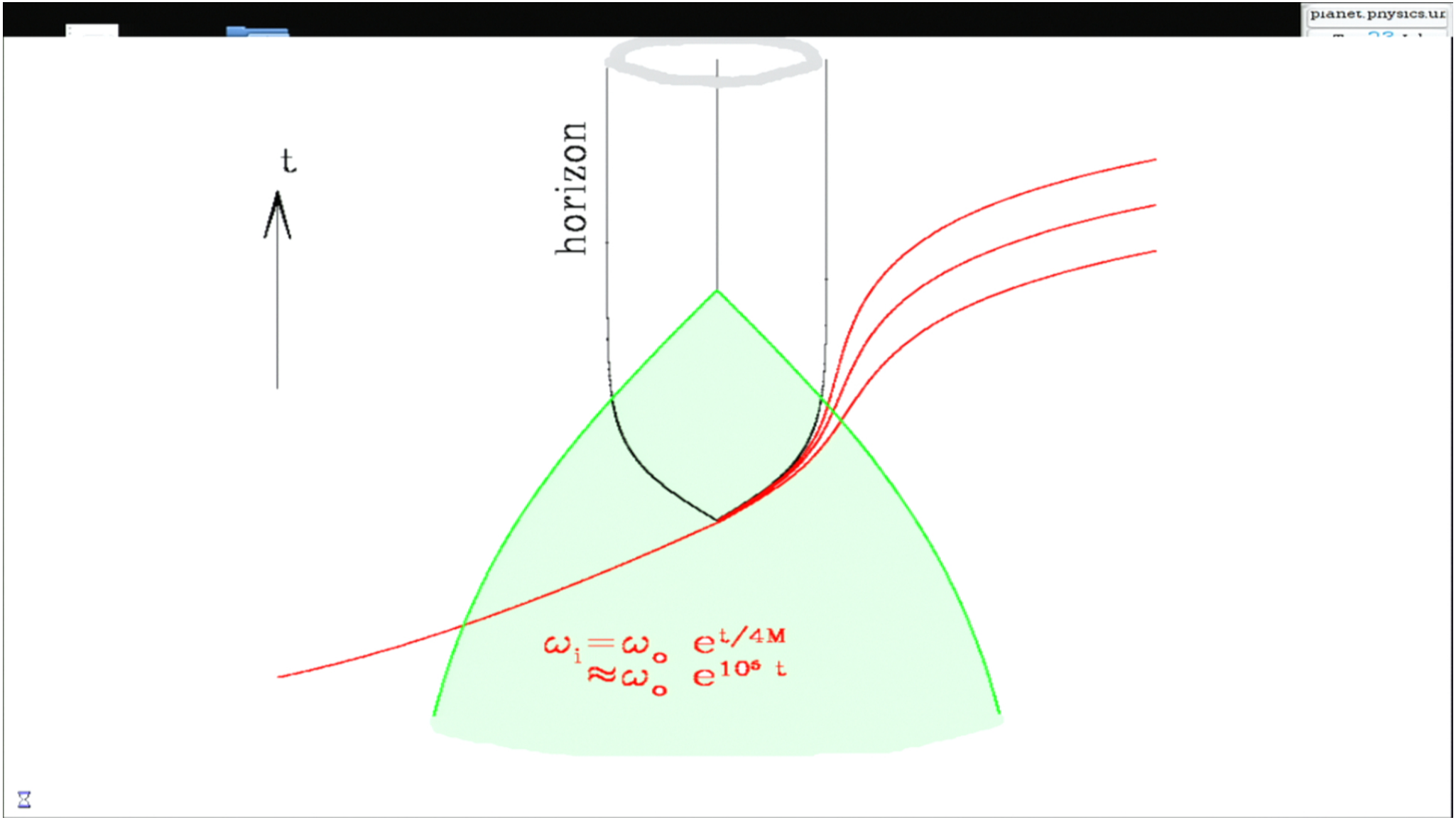
What are the internal degrees of freedom of a black hole?

Inside-- How can they affect radiation?
Outside-- What are the degrees of freedom?

Problem

Derivation makes no physical sense

Mathematically correct, physical nonsense


t
horizon
$\omega_i = \omega_o \; e^{t/4M}$
$\approx \omega_o \; e^{10^5 \, t}$

Frequencies which cause the outgoing radiation
Are absurdly high in the ingoing state.
After 1 second for solar mass black hole

e^{10^5} Any units make no difference

Experiment would be deteminant.

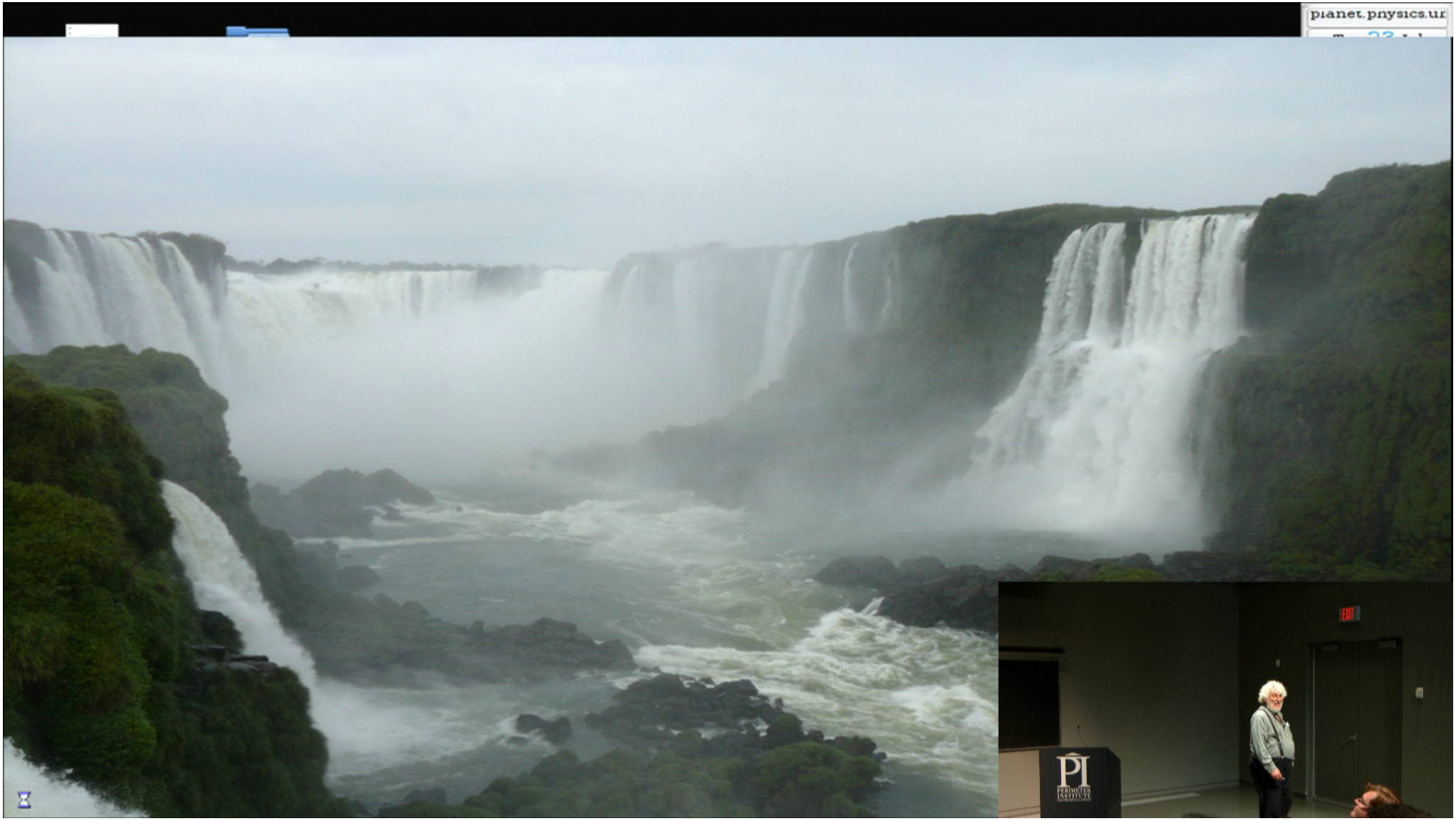
But small black holes are hard to find

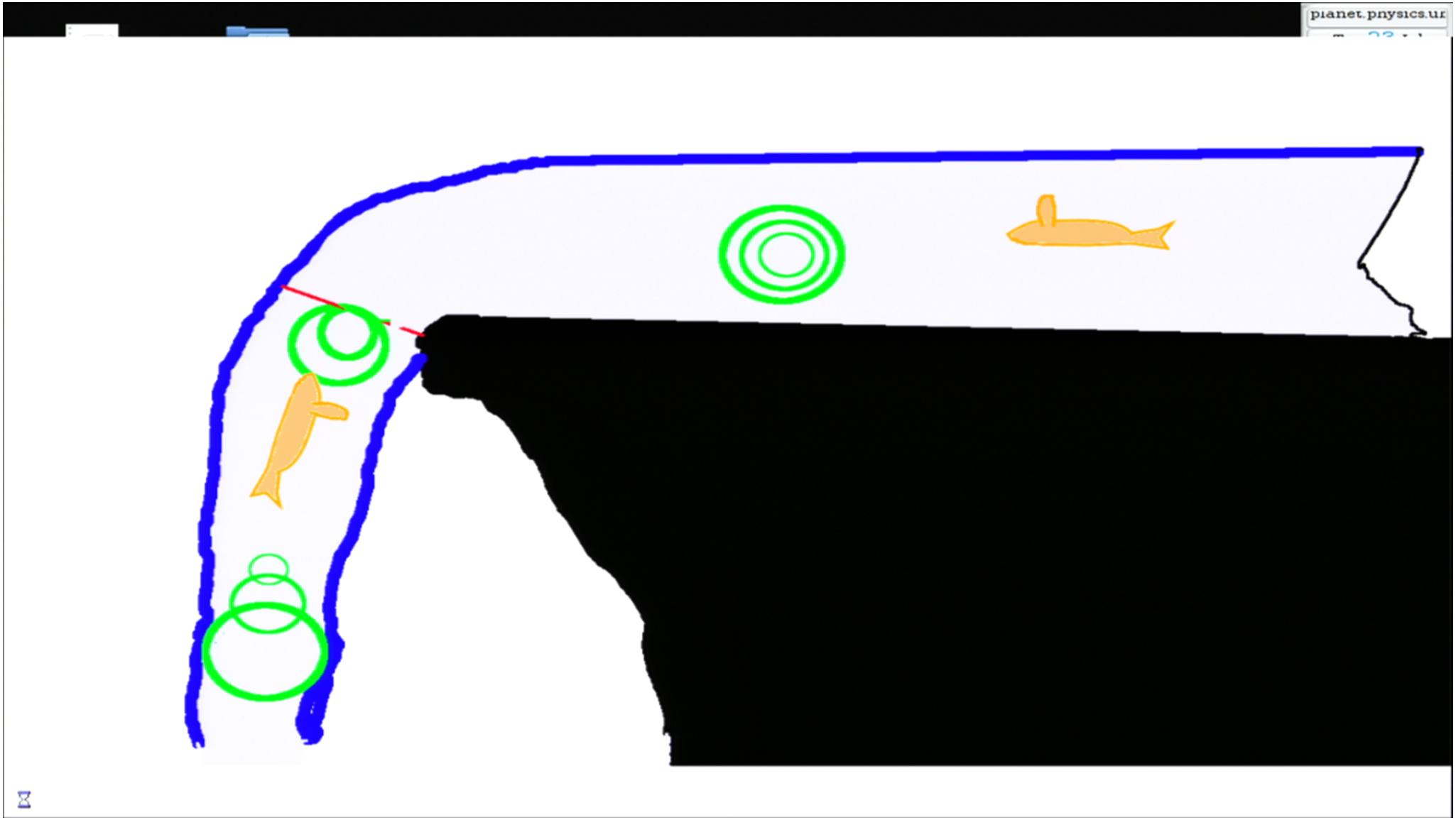
Frequencies which cause the outgoing radiation
Are absurdly high in the ingoing state.
After 1 second for solar mass black hole

e^{10^5} Any units make no difference

Experiment would be deteminant.

But small black holes are hard to find


planet.physics.ur
EXIT
PI
PERIMETER INSTITUTE


planet.physics.ur

The equation of motion of the sound waves in irrotational flowing fluid identical (in Hydrodynamic limit) to equations of massless scalar field In background metric.

$$v = \nabla\varphi \qquad \Box\varphi = 0$$

$$g_{tt} = c^2 - v^2 \qquad g_{ti} = v_i \qquad g_{ij} = \delta_{ij}$$

c is velocity of sound in fluid.

If v purely radial and of form $v = \sqrt{\frac{2M}{r}}$

Schwarzschild metric in Painleve Gullstrand coords.

Metric equivalence

The equation of motion of the sound waves in irrotational flowing fluid identical (in Hydrodynamic limit) to equations of massless scalar field In background metric.

$$v = \nabla \varphi \qquad \Box \varphi = 0$$

$$g_{tt} = c^2 - v^2 \qquad g_{ti} = v_i \qquad g_{ij} = \delta_{ij}$$

c is velocity of sound in fluid.

If v purely radial and of form $v = \sqrt{\frac{2M}{r}}$

Schwarzschild metric in Painleve Gullstrand coords.

Using the same arguments as Hawking

$$T = \left(\frac{\hbar}{k_B}\right) \frac{1}{4\pi c} \frac{d(c^2 - v^2)}{dx}$$

Temperature determined by the geometry of background Fluid flow. (c—velocity of sound, v—velocity of fluid)

Problem-- Hydrodynamic approx.
Suffers from the same ultra high freq problem.

Using the same arguments as Hawking

$$T = \left(\frac{\hbar}{k_B}\right) \frac{1}{4\pi c} \frac{d(c^2 - v^2)}{dx}$$

Temperature determined by the geometry of background Fluid flow. (c—velocity of sound, v—velocity of fluid)

Problem-- Hydrodynamic approx.
Suffers from the same ultra high freq problem.

Using the same arguments as Hawking

$$T = \left(\frac{\hbar}{k_B}\right) \frac{1}{4\pi c} \frac{d(c^2 - v^2)}{dx}$$

Temperature determined by the geometry of background Fluid flow. (c—velocity of sound, v—velocity of fluid)

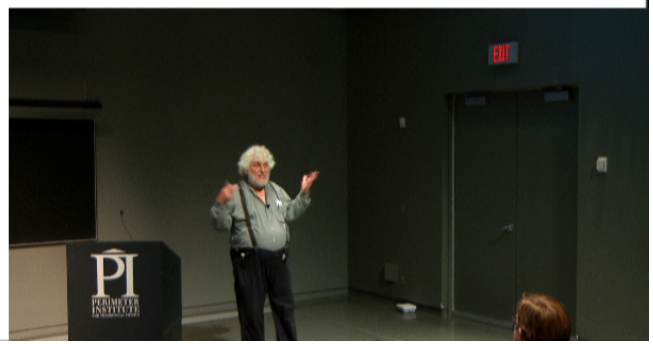
Problem-- Hydrodynamic approx.
Suffers from the same ultra high freq problem.

Atomic nature of matter-- prevents ultra high freq problem
Cannot have sound waves with wavelength
Shorter than interatomic spacing.

Does this destroy the effect?
(What is the influence of the ultra high freq. On Phenomenon?)

Atomic nature of matter-- prevents ultra high freq problem
Cannot have sound waves with wavelength
Shorter than interatomic spacing.

Does this destroy the effect?
(What is the influence of the ultra high freq. On Phenomenon?)

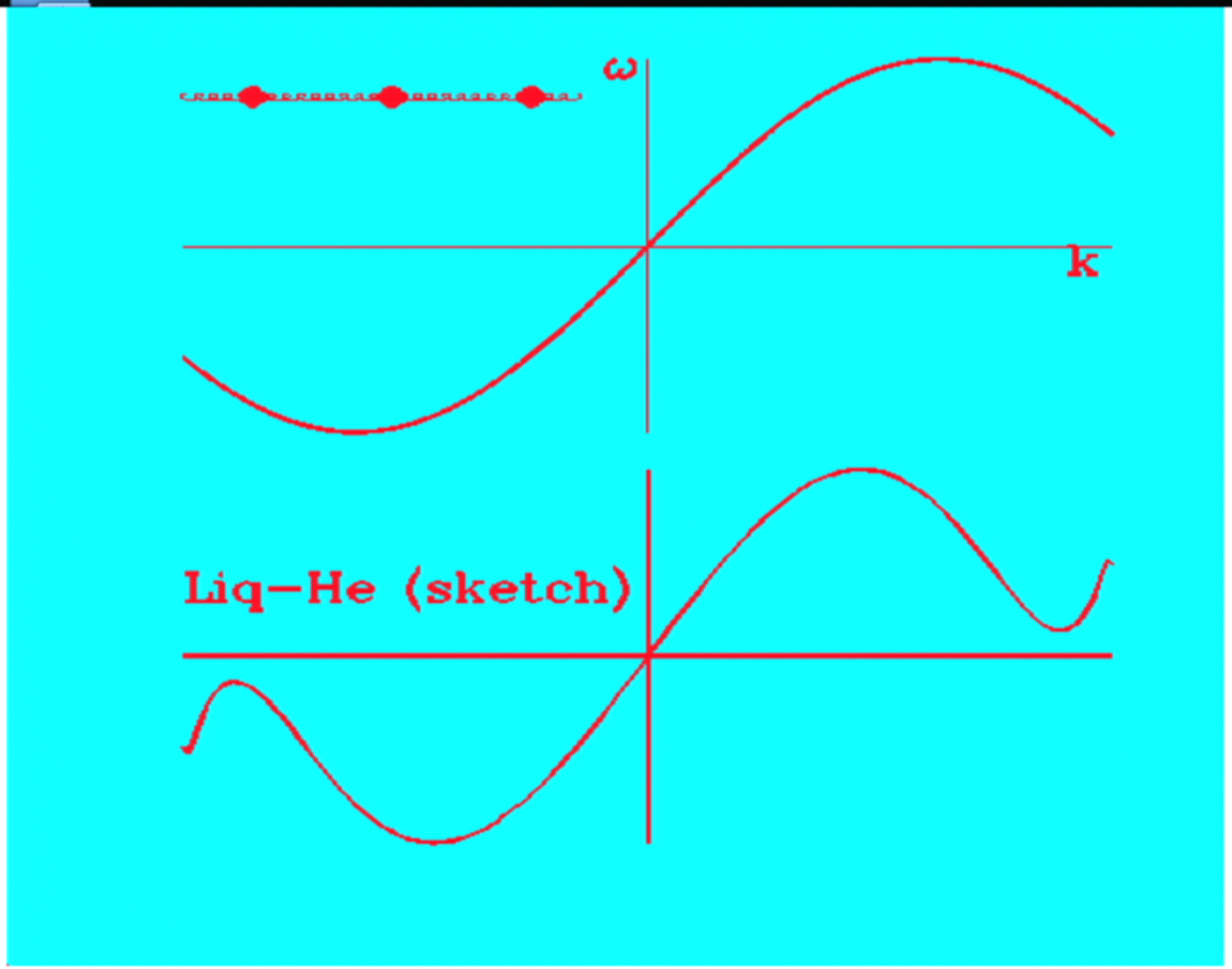


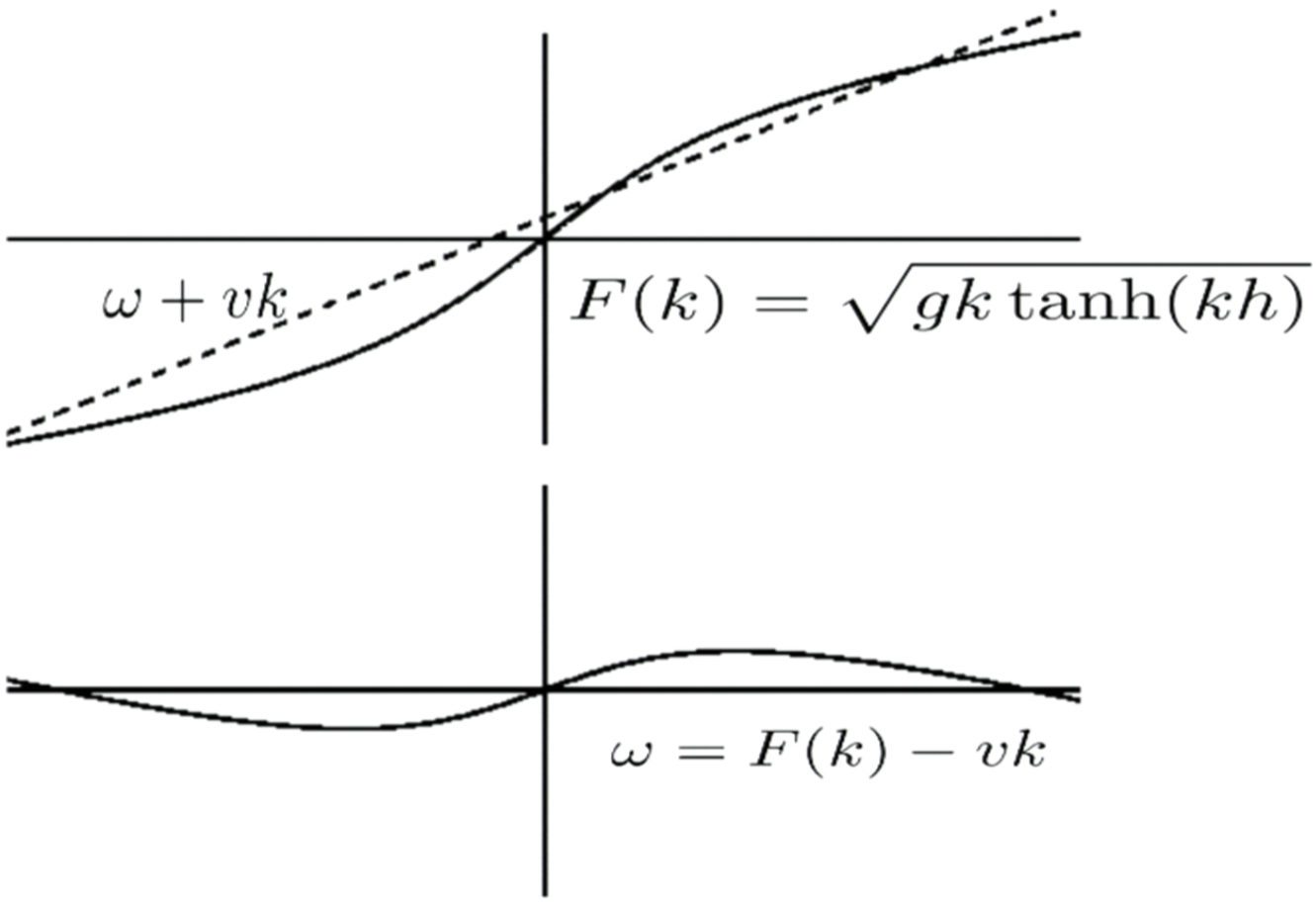
Atomic nature of matter-- prevents ultra high freq problem
Cannot have sound waves with wavelength
Shorter than inter-atomic spacing.

Does this destroy the effect?
(What is the influence of the ultra high freq. On Phenomenon?)

(Jacobson) Dispersion relation of sound waves

$$\omega + vk = F(k)$$
$$\omega = F(k) - vk$$


ω
k
Liq–He (sketch)


$\omega + vk$
$F(k) = \sqrt{gk \tanh(kh)}$
$\omega = F(k) - vk$

PHYSICAL REVIEW
LETTERS

VOLUME 46 | 25 MAY 1981 | NUMBER 21

Experimental Black-Hole Evaporation?

W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.

PACS numbers: 04.60.+n, 04.80.+z, 47.90.+a, 97.60.Lf

Black-hole evaporation[1,2] is one of the most surprising discoveries of the past ten years. Black holes emit thermal radiation with a temperature given by $\hbar c^3/8\pi kGM$, and thus seem to combine quantum mechanics and gravitation to equation at small scales on the evaporation process, and one might even contemplate the experimental investigation of the thermal emission process.

The model of the behavior of quantum field in a

2010

Experimental Black-Hole Evaporation

W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a t
transso

PACS n

Black-hole evapo
surprising discove
Black holes emit t
perature given by
combine quantum

PRL **106,** 021302 (2011) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2011

Measurement of Stimulated Hawking Emission in an Analogue System

Silke Weinfurtner,[1] Edmund W. Tedford,[2] Matthew C. J. Penrice,[1] William G. Unruh,[1] and Gregory A. Lawrence[2]
[1]*Department of Physics and Astronomy, University of British Columbia, Vancouver, Canada V6T 1Z1*
[2]*Department of Civil Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, Canada V6T 1Z4*
(Received 30 August 2010; published 10 January 2011)

Hawking argued that black holes emit thermal radiation via a quantum spontaneous emission. To address this issue experimentally, we utilize the analogy between the propagation of fields around black holes and surface waves on moving water. By placing a streamlined obstacle into an open channel flow we create a region of high velocity over the obstacle that can include surface wave horizons. Long waves propagating upstream towards this region are blocked and converted into short (deep-water) waves. This is the analogue of the stimulated emission by a white hole (the time inverse of a black hole), and our measurements of the amplitudes of the converted waves demonstrate the thermal nature of the conversion process for this system. Given the close relationship between stimulated and spontaneous emission, our findings attest to the generality of the Hawking process.

DOI: 10.1103/PhysRevLett.106.021302 PACS numbers: 04.70.Dy, 04.60.−m, 04.62.+v, 47.35.Bb

Analogy: Waves in fluids (sound, surface,...)
Electromagnetic waves in waveguides, fibres

Obey same equations as Hawking's fields at low freq.

Obey different equations than Hawking's at short wavelengths

Can use differences to test dependence of effect
(Thermal emission) on short wavelength physics.
Does Hawking effect really depend on ultra short physics?

Amplifier Noise

Haus Mullen (1962) – Any amplifier must produce quantum noise.

$$Y = A\,x \qquad P_Y = A\,p$$

$$[\,Y\,,\,P_Y\,] = \; i\,(A^2)$$

Amplifier Noise

Haus Mullen (1962) – Any amplifier must produce quantum noise.

$$Y = A\,x + B\,q \qquad P_Y = A\,p - B\,\theta$$

$$Z = A\,q + B\,x \qquad P_Z = A\,\theta - B\,p$$

$$[\,Y\,,\,P_Y\,] = i\,(A^2 - B^2) = i$$

The coeff **A and B** are classically determined

Quantum Noise: $N = \mathbf{B}^2$ and "Thermal"

Reduced density matrix $\rho = e^{\Lambda\,(P^2 + Y^2)/2}$ $\quad ,\Lambda = \ln(|\mathbf{B}|^2/|\mathbf{A}|^2)$

If $\Lambda \propto \omega$ –Thermal spectrum

Amplifier Noise

Haus Mullen (1962) – Any amplifier must produce quantum noise.

$$Y = A\,x + B\,q \qquad P_Y = A\,p - B\,\theta$$

$$Z = A\,q + B\,x \qquad P_Z = A\,\theta - B\,p$$

$$[\,Y\,,\,P_Y\,] = i\,(A^2 - B^2) = i$$

The coeff **A and B** are classically determined

Quantum Noise: $N = \mathbf{B}^2$ and "Thermal"

Reduced density matrix $\rho = e^{\Lambda\,(P^2 + Y^2)/2}$ $\quad ,\Lambda = \ln(|\mathbf{B}|^2/|\mathbf{A}|^2)$

If $\Lambda \propto \omega$ –Thermal spectrum

Norm for Linear system

$$< q,q > = i\ (q^{*}\ p - p^{*}\ q)$$

Norm is not positive definite (solution q* has opposite norm)

$$Q = a\ q + a^{\dagger} q^{*}$$

$$<\varphi\ ,\ \varphi\ > =\ i \int (\varphi * \pi - \pi * \varphi\ )\ d^{3}x$$

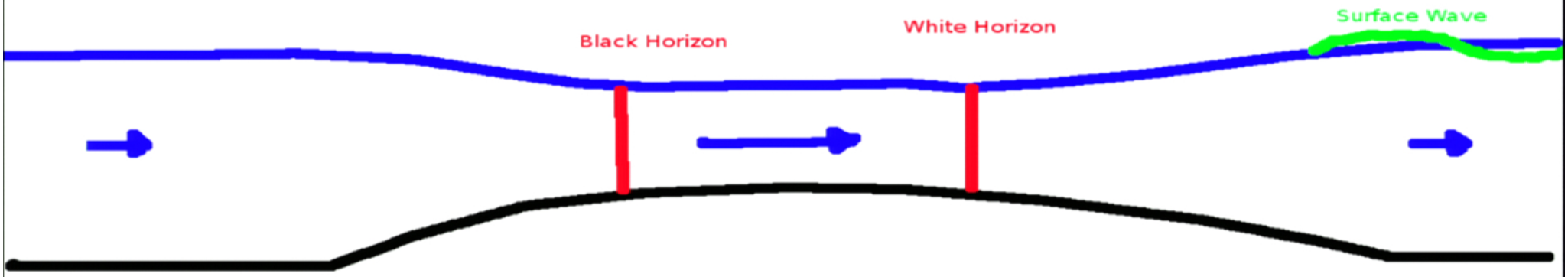
$$\Phi = \sum\ (a_i\ \varphi_i + a_i^{\dagger}\ \varphi_i^{*}\ )$$

Quantum Noise is completely determined Classically

Conversion of incoming positive norm (frequency) into Combination of positive and negative norm outgoing Determines quantum noise.

Black hole-- Incoming waves ultra high wavenumber
Outgoing waves low wavenumber

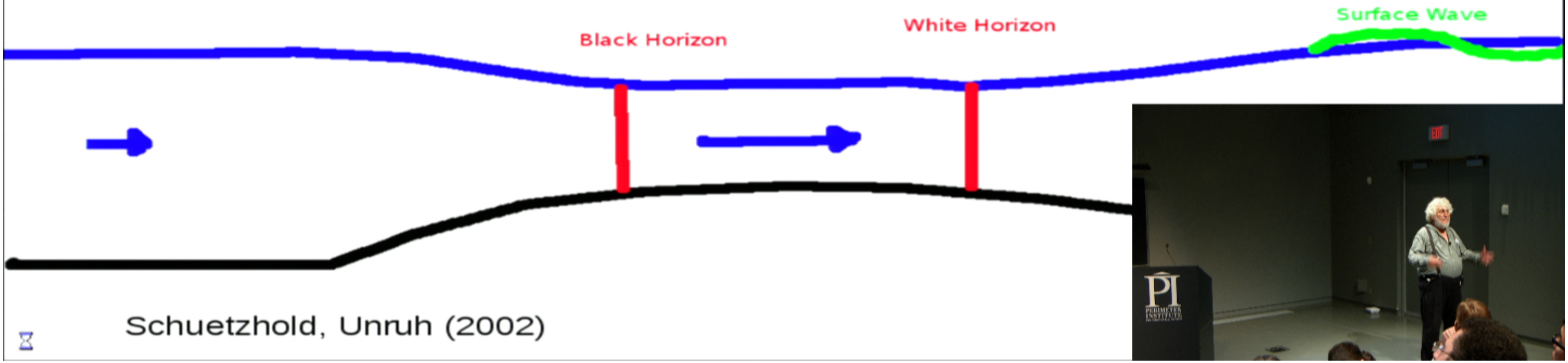
White hole-- Time reverse of black hole (Nothing can go Into a white hole)
Incoming waves low wave number. Outgoing waves high wavenumber



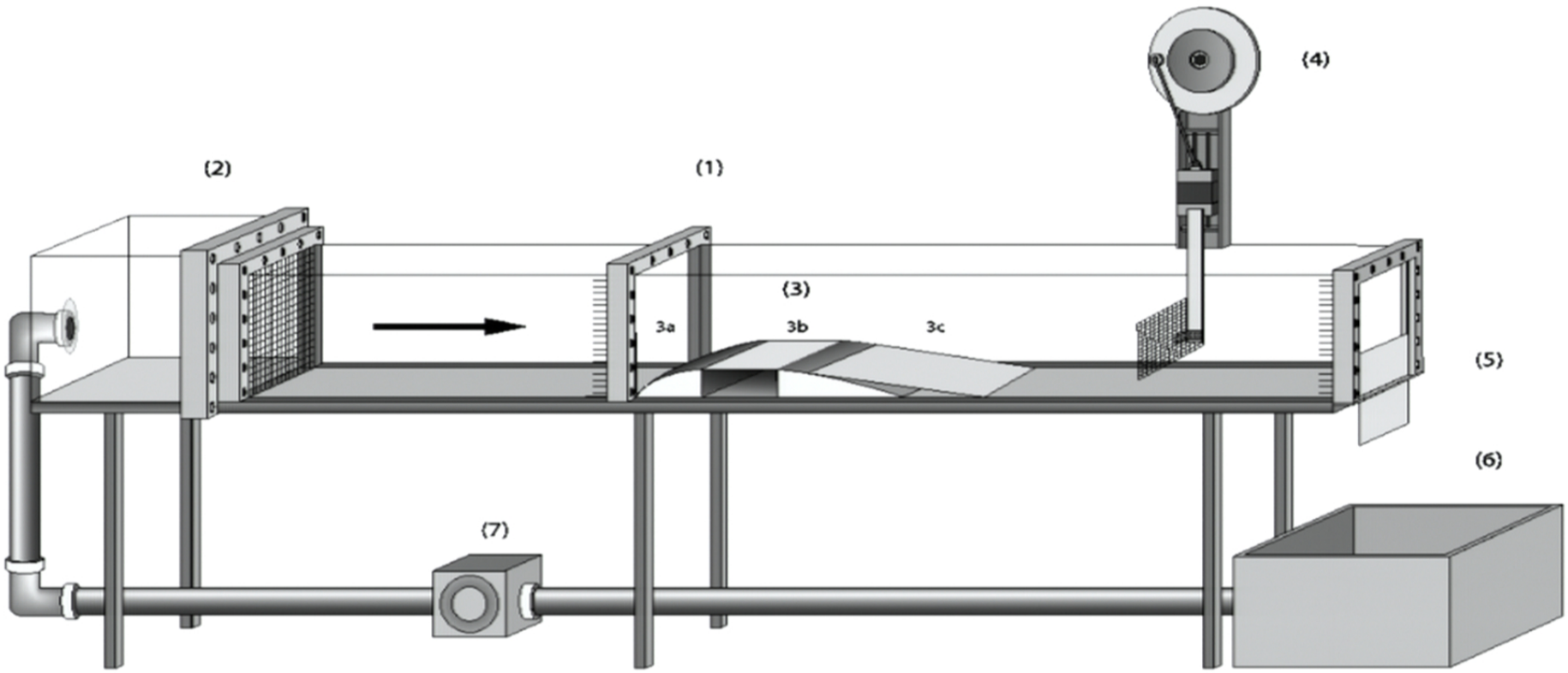
Schuetzhold, Unruh (2002)

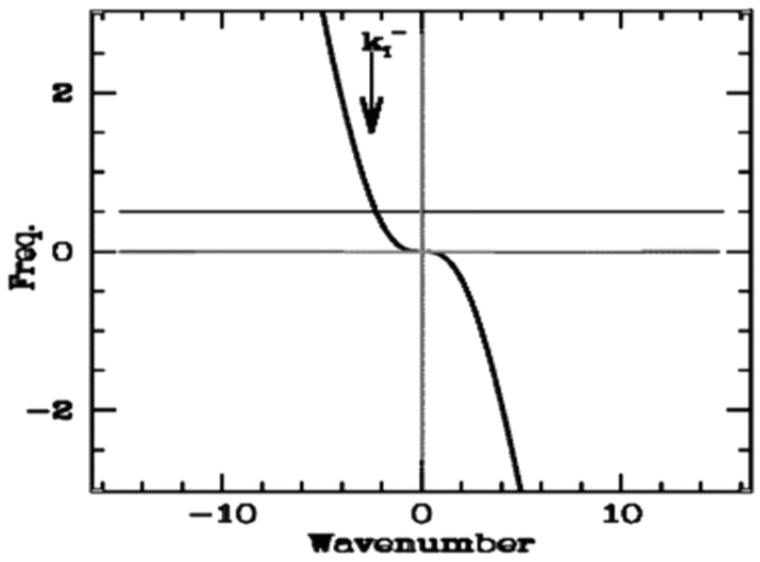
Black hole-- Incoming waves ultra high wavenumber
Outgoing waves low wavenumber

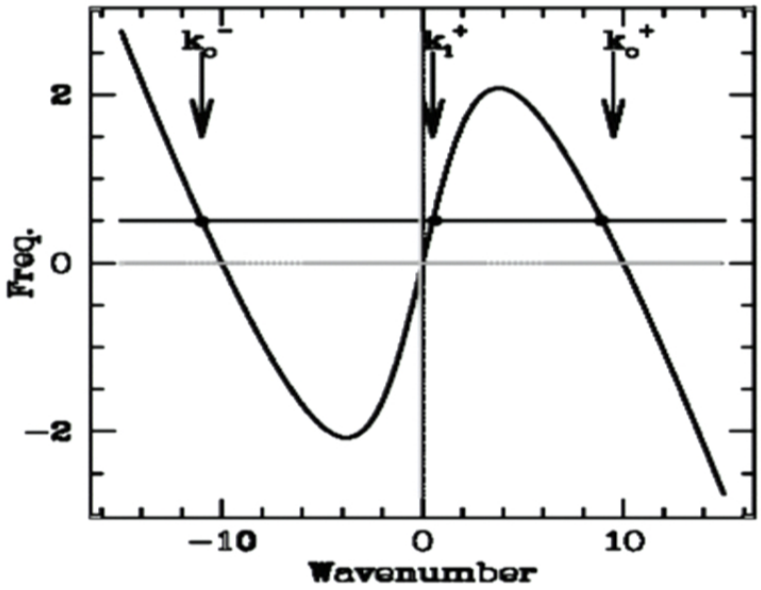
White hole-- Time reverse of black hole (Nothing can go Into a white hole)
Incoming waves low wave number. Outgoing waves high wavenumber

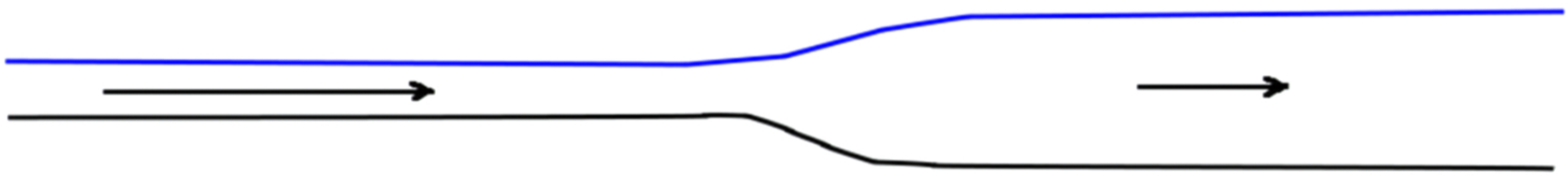


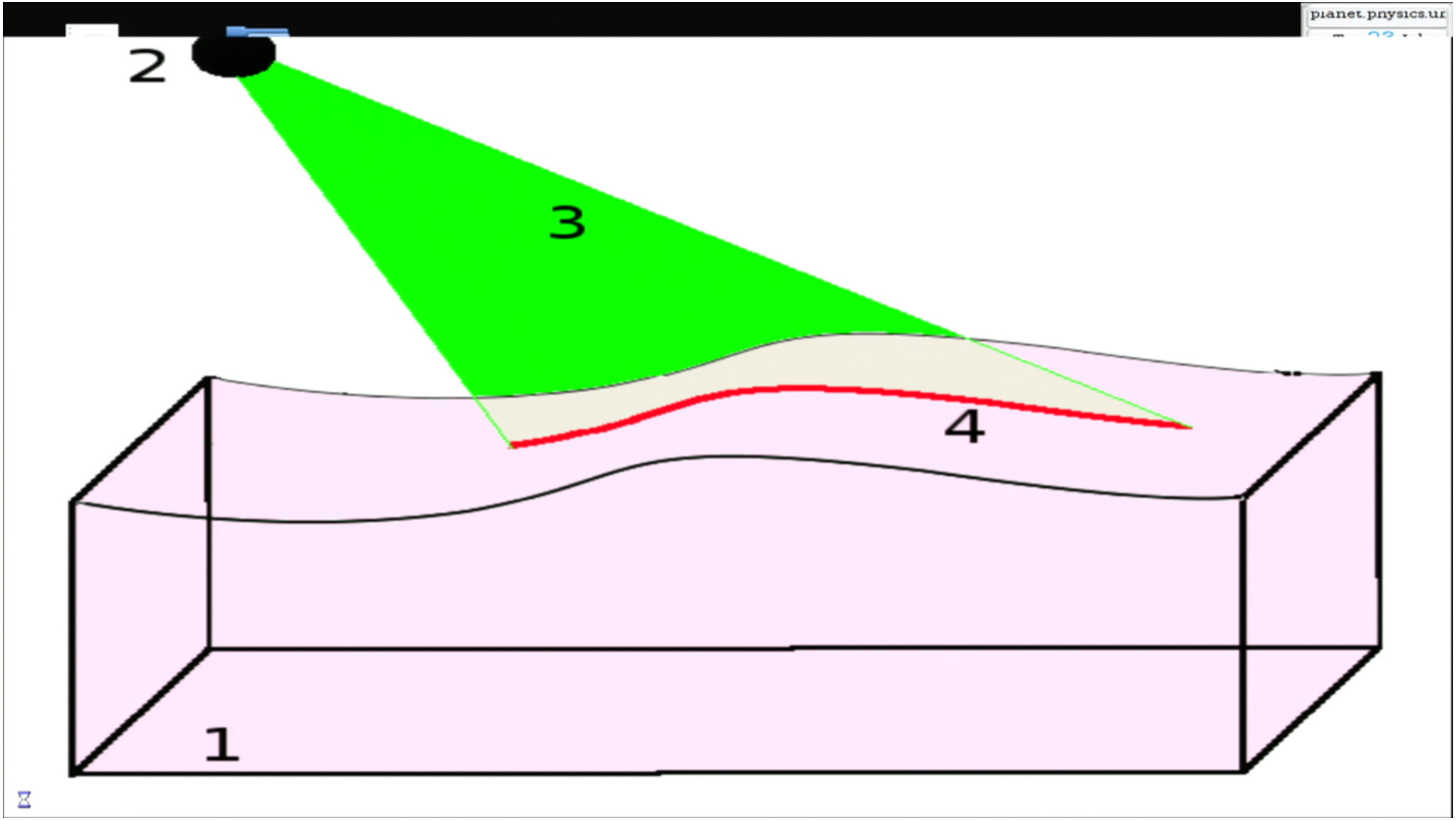
Schuetzhold, Unruh (2002)

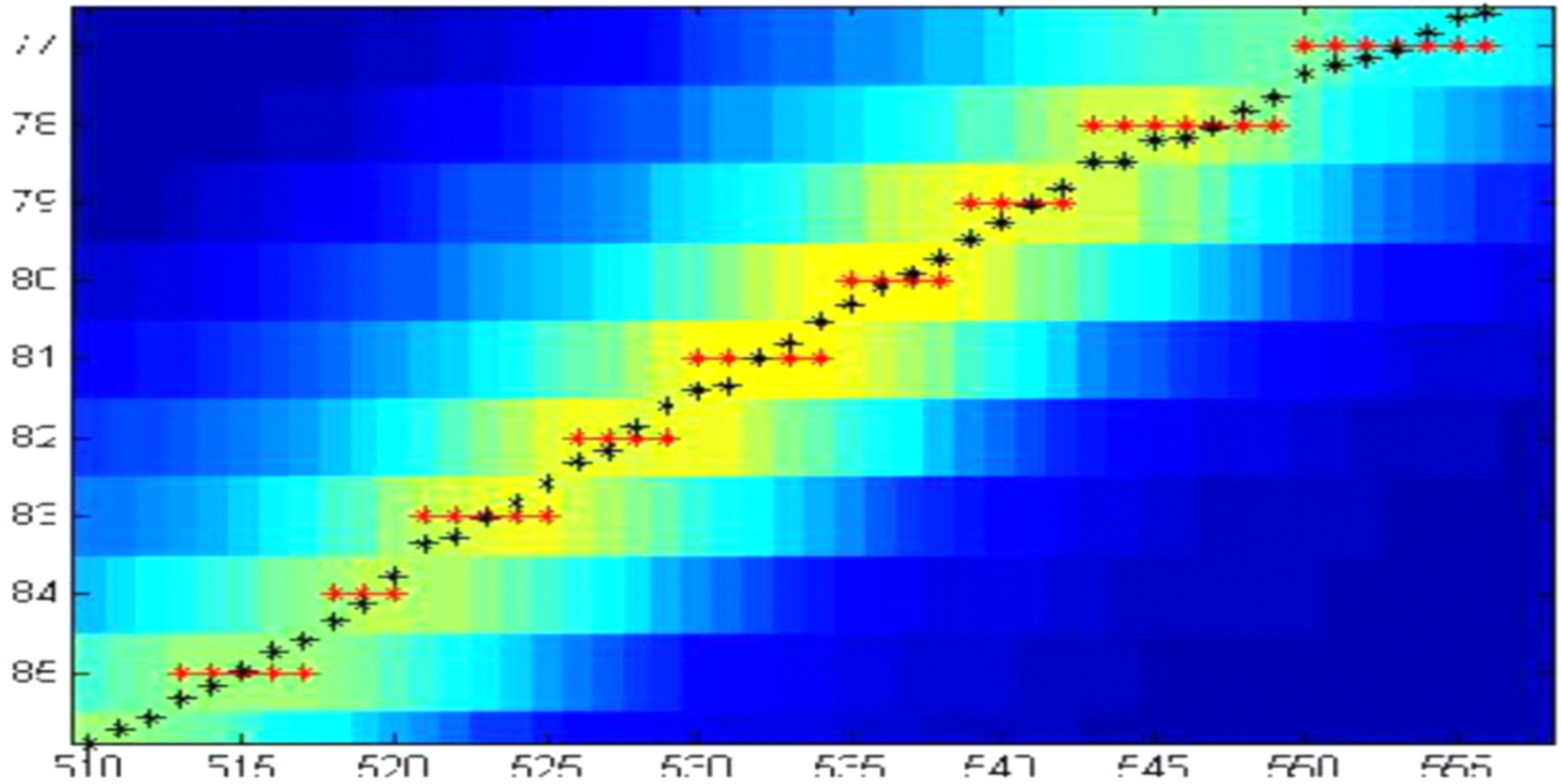

(2)
(1)
(4)
(3)
3a
3b
3c
(5)
(6)
(7)


k_1^-
2
0
−2
Freq.
−10
0
10
Wavenumber

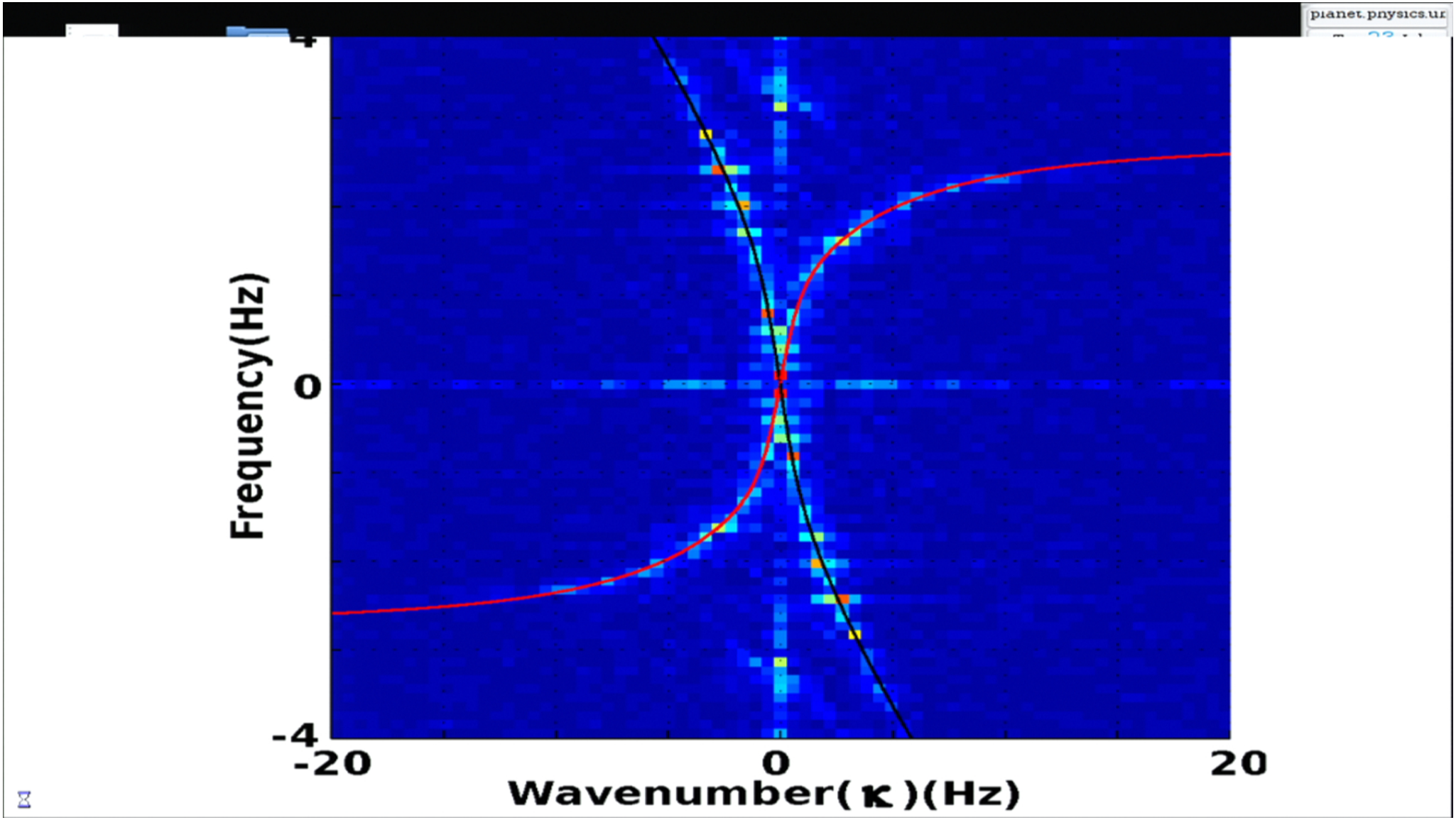

k_0^-
k_1^+
k_0^+
2
0
−2
Freq.
−10
0
10
Wavenumber

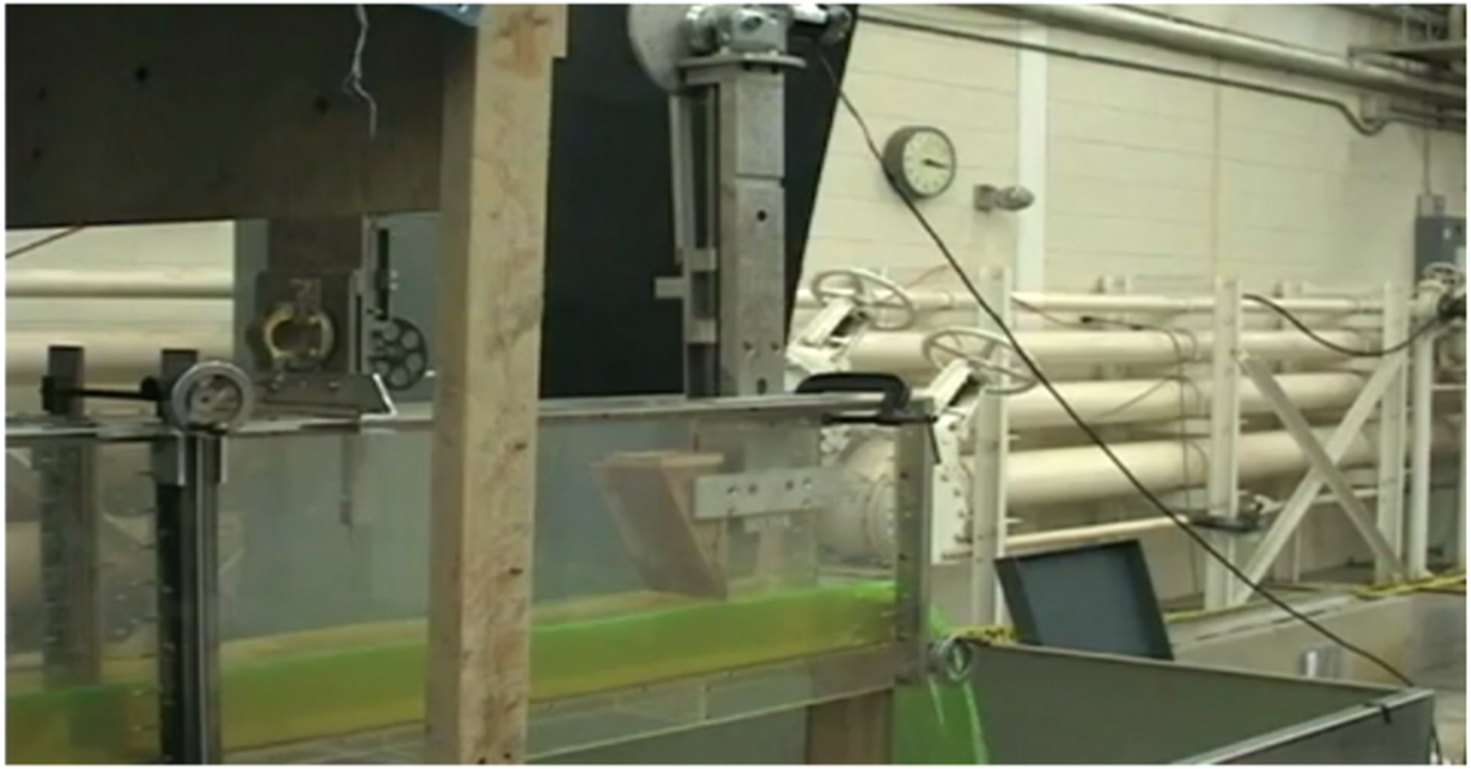


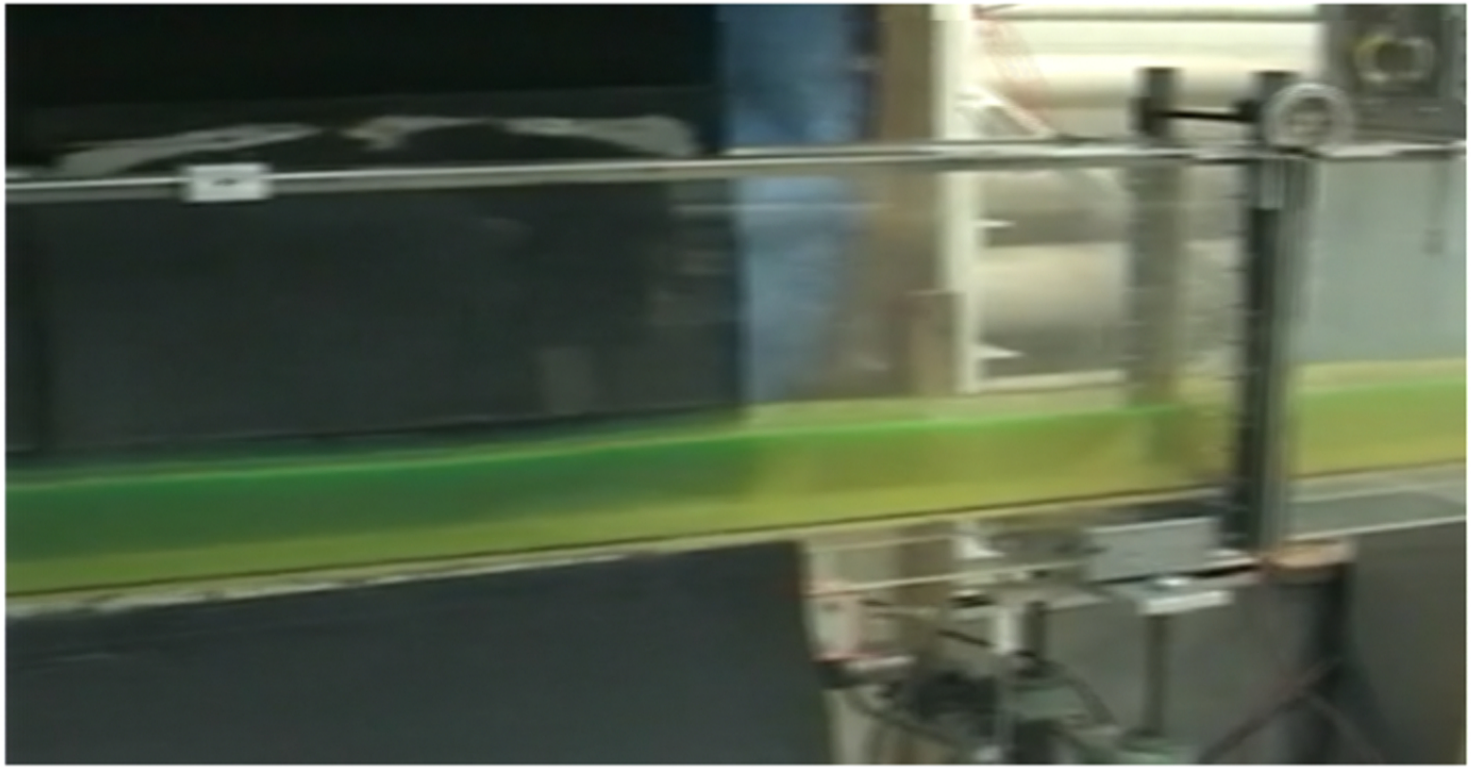

2
3
4
1

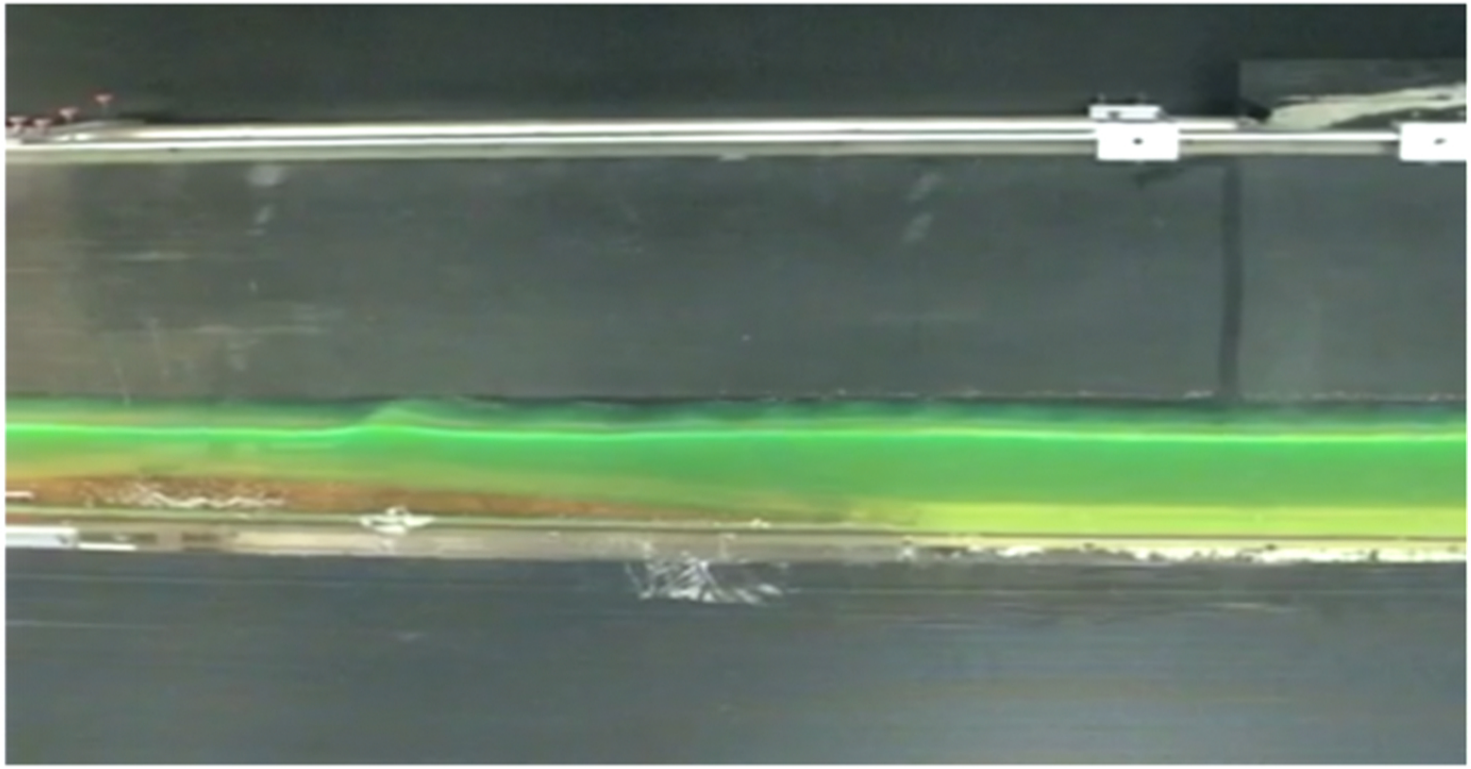


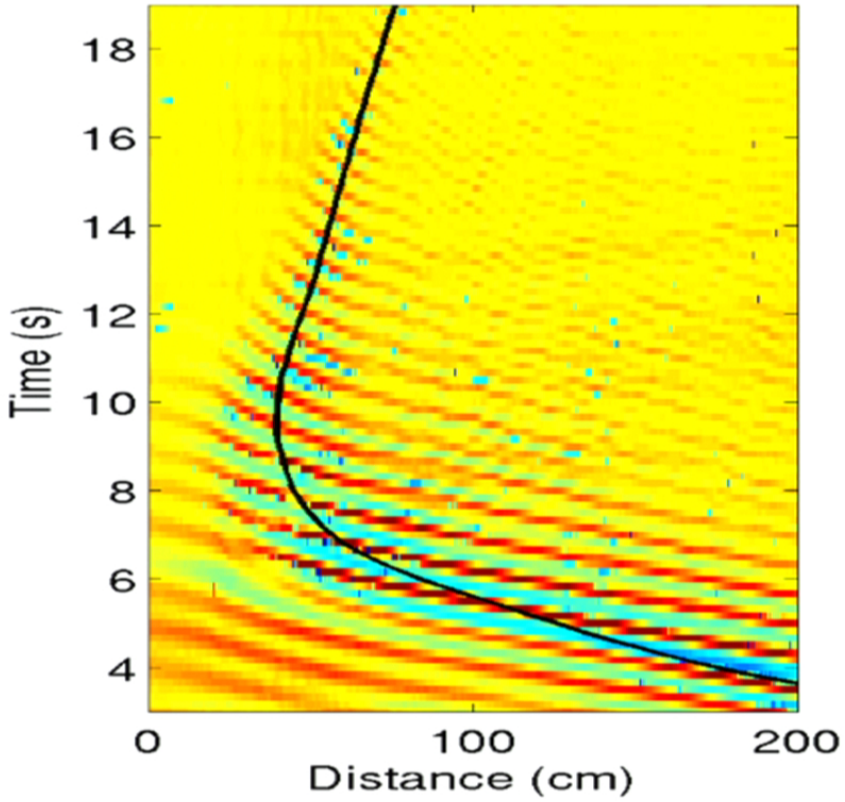
Sub Pixel Resolution

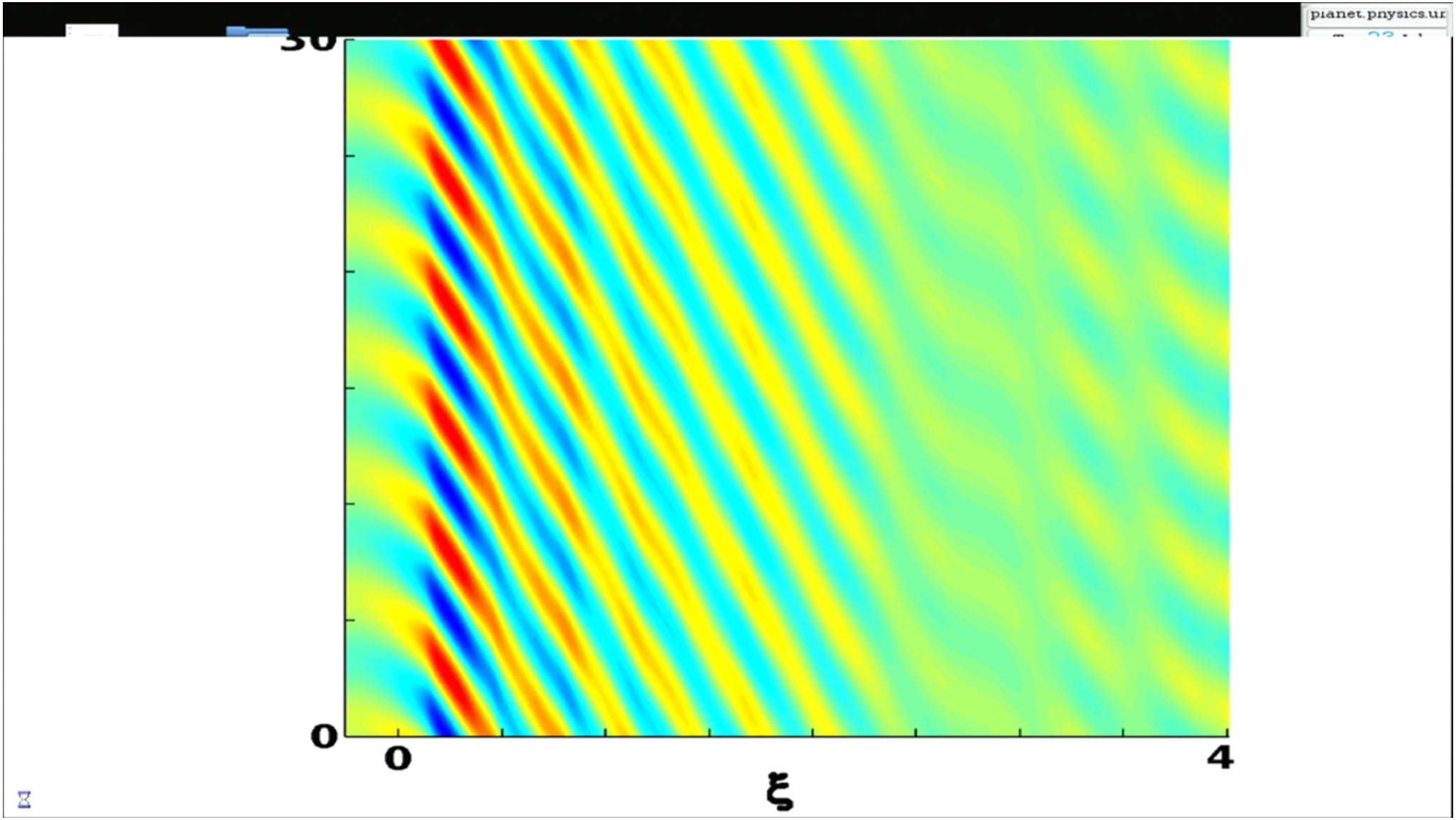

Frequency(Hz)
4
0
-4
-20
0
20
Wavenumber(κ)(Hz)

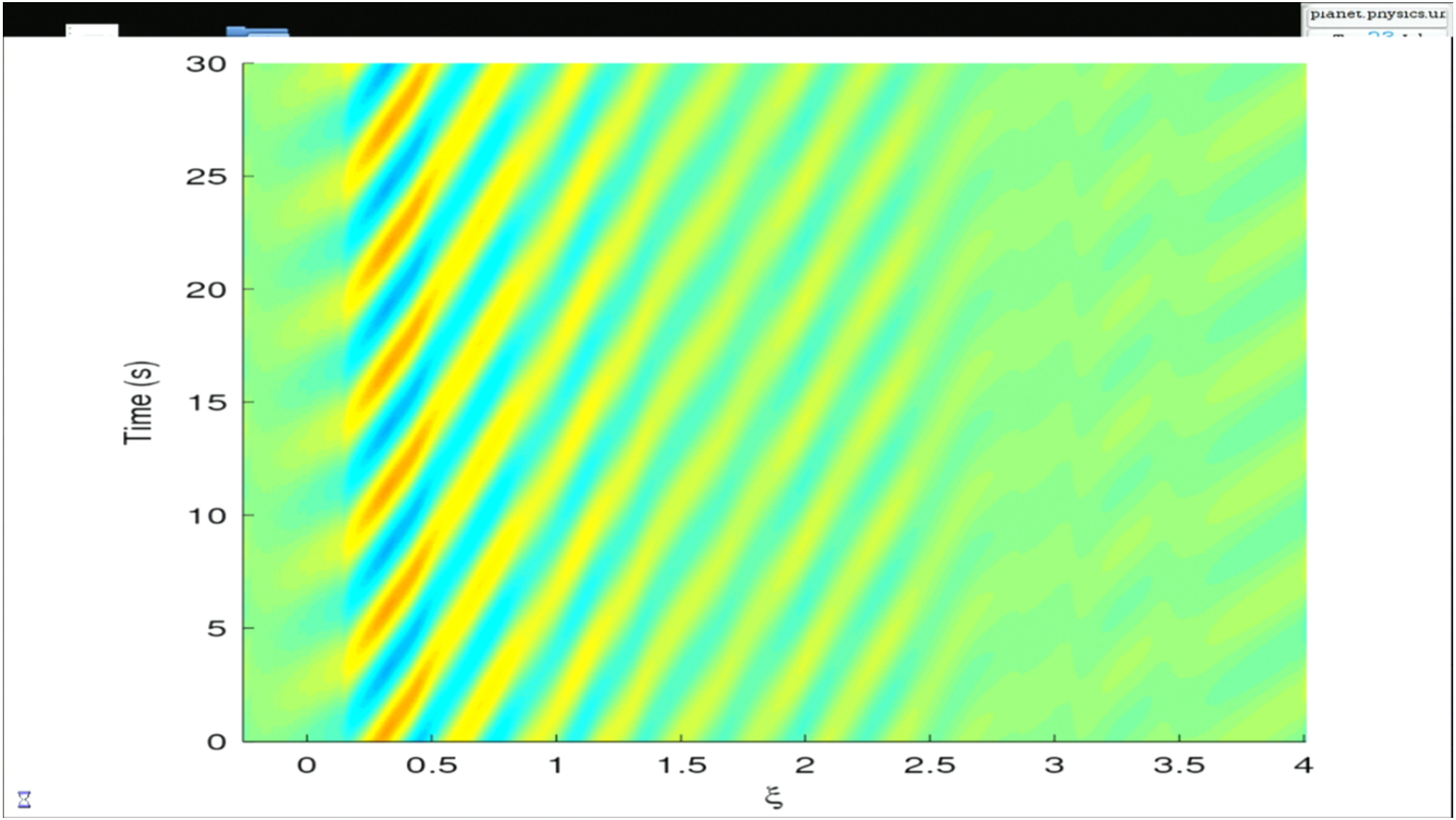


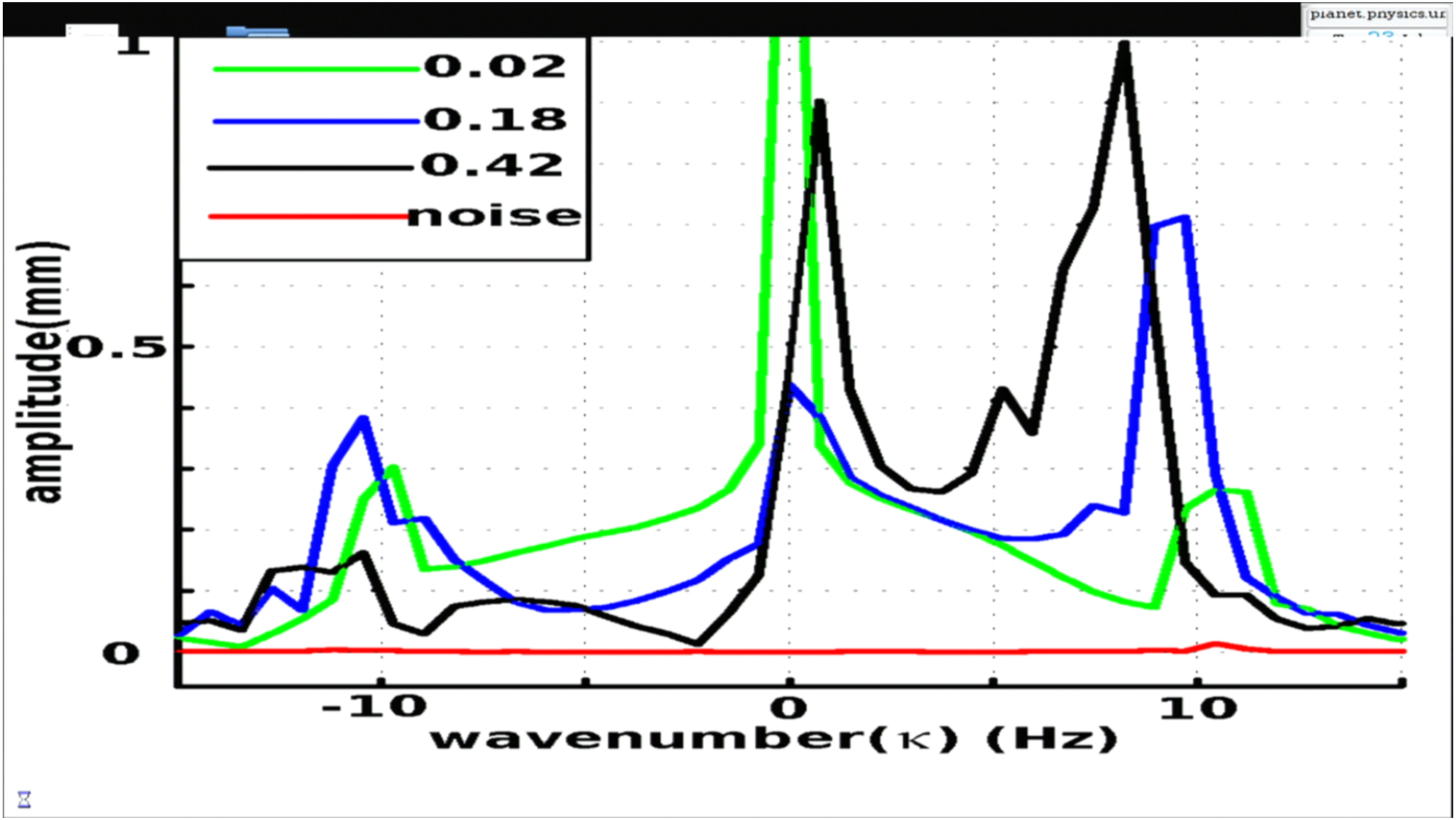


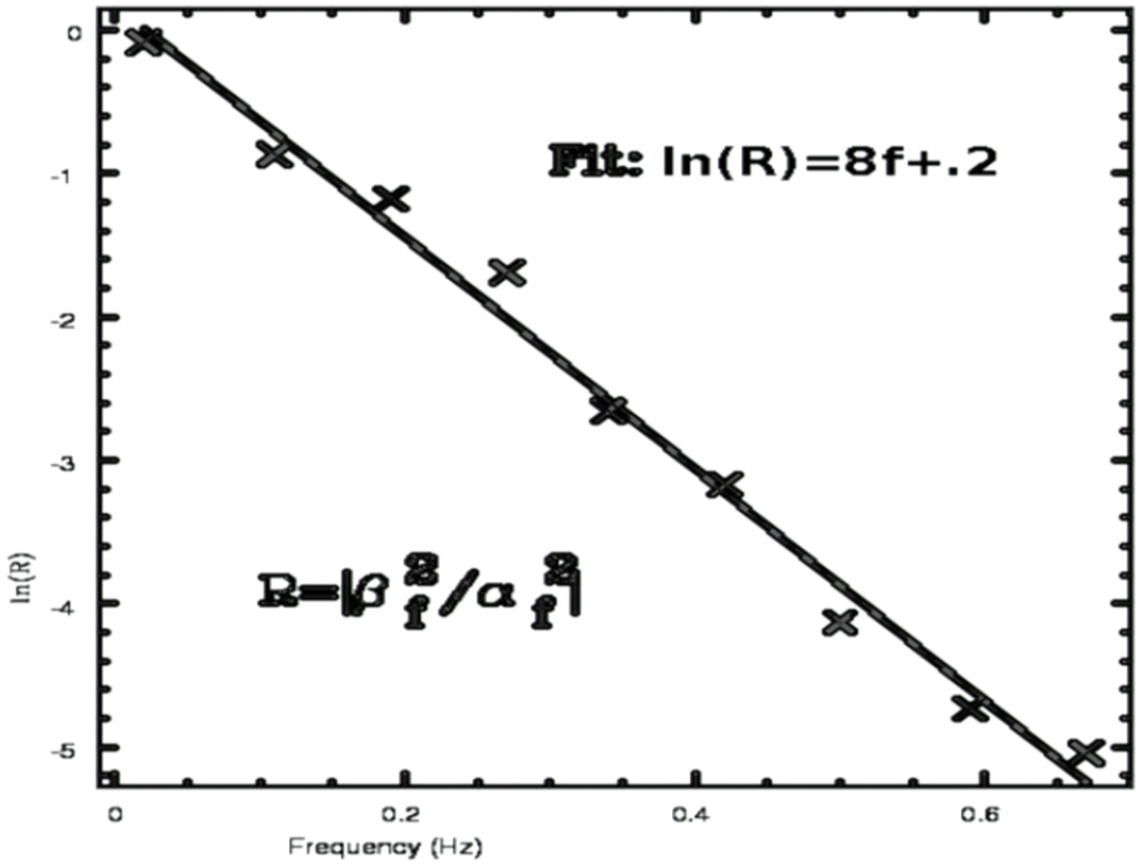



18
16
14
12
10
8
6
4
Time (s)
0
100
200
Distance (cm)


planet.physics.ur
30
0
0
4
ξ


Time (s)
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
ξ

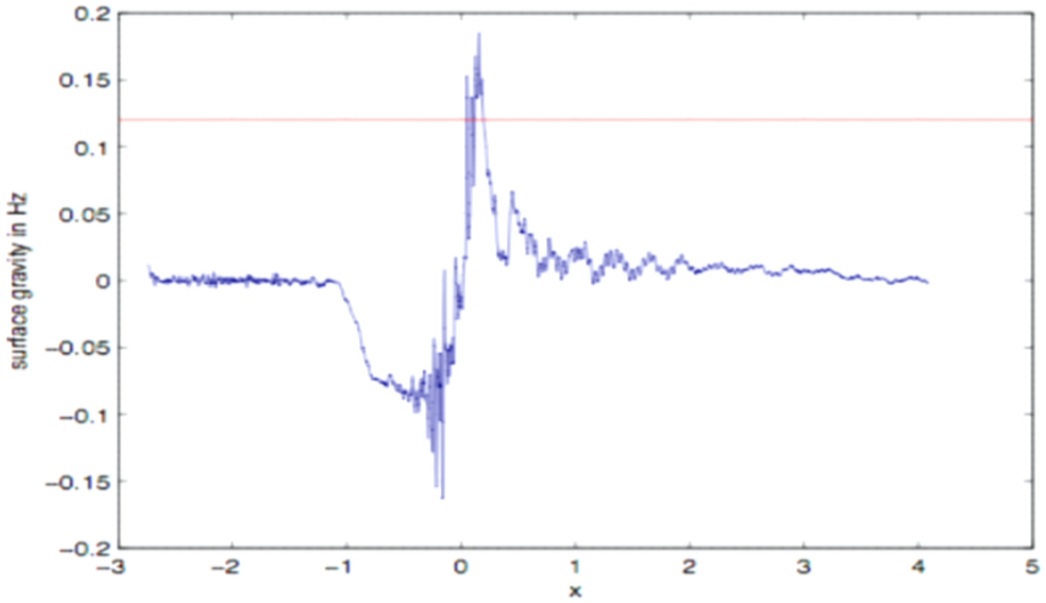

planet.physics.ur
0.02
0.18
0.42
noise
amplitude(mm)
1
0.5
0
-10
0
10
wavenumber(κ) (Hz)


Fit: ln(R)=8f+.2
R=|β_f^2/α_f^2|
ln(R)
0
-1
-2
-3
-4
-5
0
0.2
0.4
0.6
Frequency (Hz)

- Ongoing work:

$$|\beta_\omega|^2 = e^{-\frac{2\pi\omega}{g_{\mathrm{H}}}}|\alpha_\omega|^2$$

$$g_{\mathrm{H}} = \frac{1}{2}\frac{\partial(c^2 - v^2)}{\partial n}$$

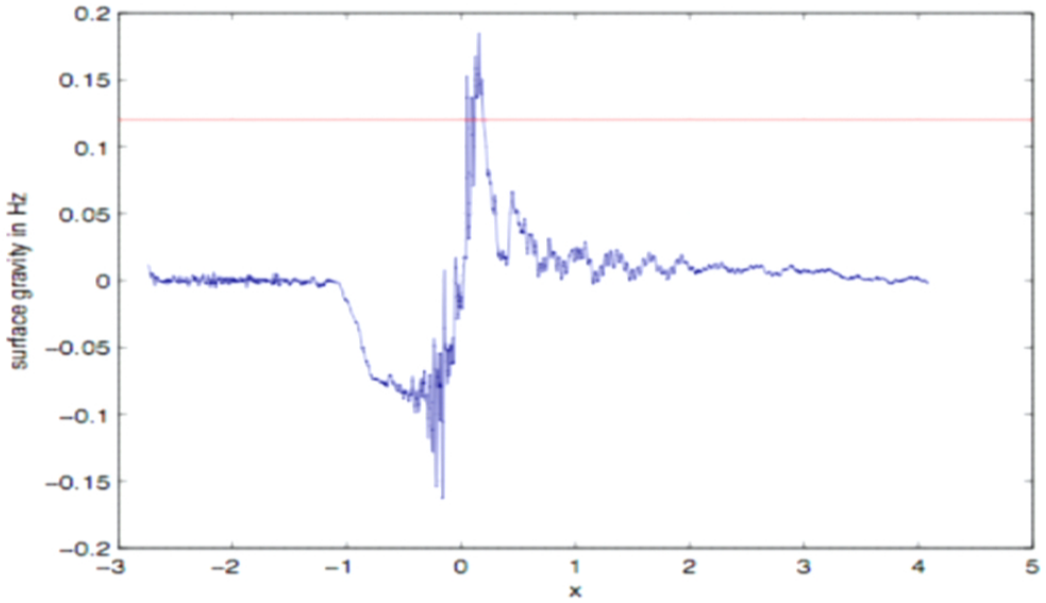


Evaluated on Horizon—Exactly where is Horizon?

- Ongoing work:

$$|\beta_\omega|^2 = e^{-\frac{2\pi\omega}{g_{\mathrm{H}}}}|\alpha_\omega|^2$$

$$g_{\mathrm{H}} = \frac{1}{2}\frac{\partial(c^2 - v^2)}{\partial n}$$



Evaluated on Horizon—Exactly where is Horizon?

What is Quantum about this experiment?

a) As argued, for a linear model, the quantum behaviour entirely determined by classical behaviour

b) If we spend $10M and saw quantum surface waves what would this show?

Quantum mechanics is true. -- Commutation relations exist.
Does anyone doubt it?

Conclusion:

The (white) hole horizon of the fluid in the flume to surface gravity waves emits quantum radiation with a **Thermal Spectrum**

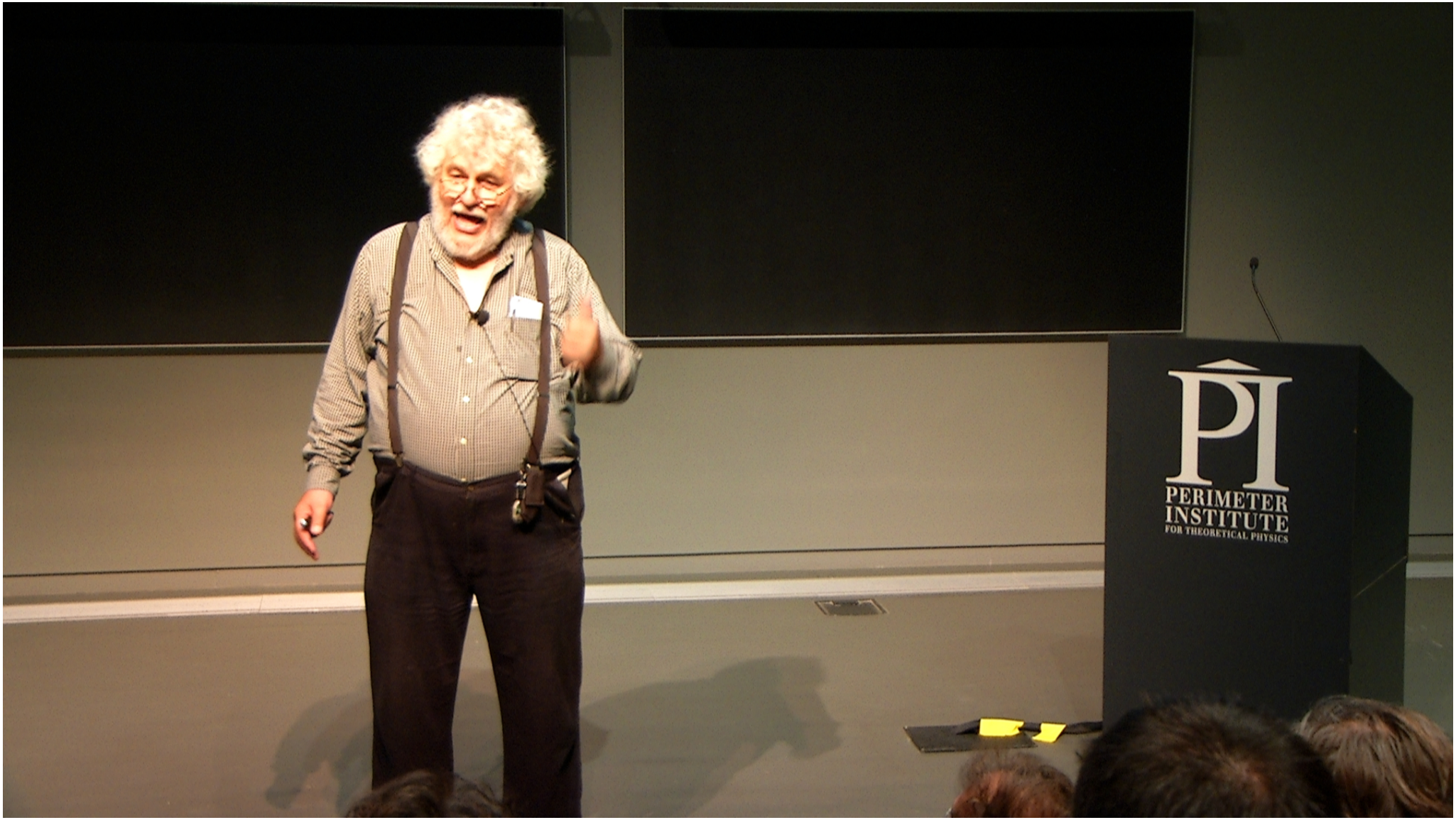
the temperature is about 6×10^{-12} K

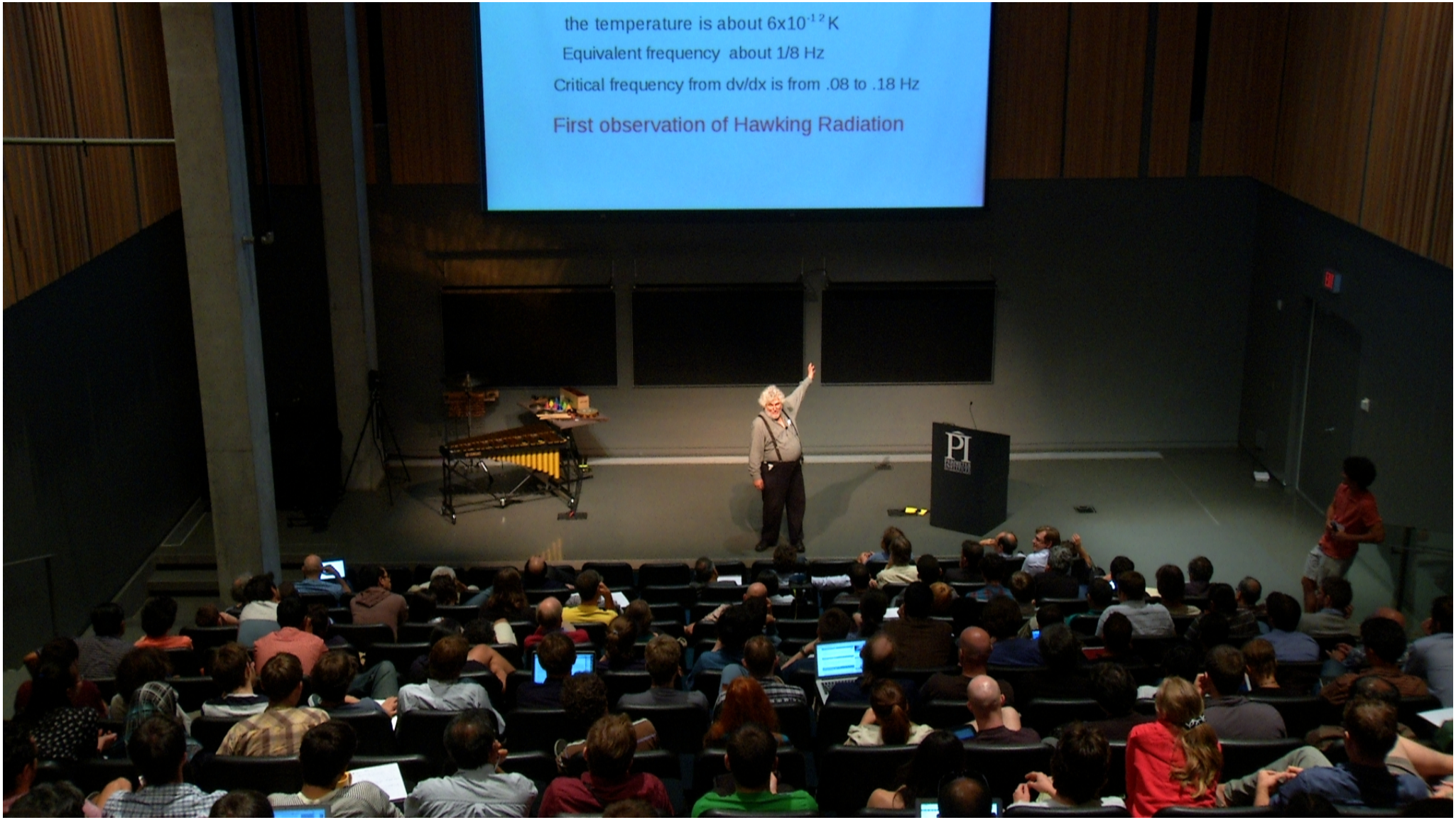
Equivalent frequency about 1/8 Hz

Critical frequency from dv/dx is from .08 to .18 Hz

First observation of Hawking Radiation


PERIMETER
INSTITUTE


PI
PERIMETER
INSTITUTE
FOR THEORETICAL PHYSICS


the temperature is about 6x10-12 K
Equivalent frequency about 1/8 Hz
Critical frequency from dv/dx is from .08 to .18 Hz
First observation of Hawking Radiation